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Distribution Networks as Complex Dynamic Systems
New Perspective for Monitoring Them

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***Abstract*—In this paper, we set out our arguments for a new approach to control electrical distribution networks making them more robust and flexible and giving them the ability to adapt themselves to the evolution of the way we consume and produce electricity.**

In the first part of the paper, the current state of the distribution network is presented as well as the motivations to move from classical control strategies to innovative ones. Then, the concept of Smart Grid and the associated challenges are presented. Finally, the Adaptive Multi-Agent System approach is exposed as well as the benefits it can have for the Smart Grid.

I. Introduction

A. Current Distribution Network

Current electrical networks are divided in three layers: the transmission network, the sub-transmission network and the distribution network. The transmission network is composed of producers such as power plants which provide high voltage electricity to a meshed network at a national-scale. The sub-transmission network transmits the electricity from transmission networks to distributions networks at a regional-scale. Distribution networks provide electricity to consumer. Unlike in the transmission and sub-transmission networks, the energy flow in distribution networks is unidirectional. In this paper, we propose a new approach to handle all changes (such as the massive introduction of decentralized producers and the evolution of the way we consume energy) that may occur in electrical distribution networks. A distribution network is the part of an electrical network intended to distribute electricity from sub-transmission grid to low or medium voltage consumers. Figure 1 represents the flow of energy in historical networks between the transmission network, the sub-transmission network and the distribution network.

Electrical distribution networks have always been built with a radial structure. This is the most intuitive and easy to manage solution in which there is some producers which provide electricity to consumers through unidirectional lines. This allows to easily monitor and control the network. This is particularly true for voltage regulation: to avoid blackouts, it is mandatory to ensure that the voltage in every point of the network is within a specific range. The fact that there is only one production point guarantees that the voltage is strictly descending along the network. Thus, it is possible to monitor the voltage of the whole network by observing the voltage at the source substation and the voltages at the furthest points from the source substation.

B. Openness of the Electrical Market

Our need in electricity is constantly growing. The network is then expected to be able to produce and distribute more electricity as our needs evolve. In anticipation, electrical networks have been oversized notably by installing lines able to support more than needed. This strategy have shown good results as the electrical network is currently stable and have very few interruptions. However, during the last years, there is a willingness of opening the electricity market to move from a national/regional control made by a unique entity to a local control made by multiple private entities. Thus, we now see new producers directly connected to the main network and notably renewable energy generators. Obviously, to maximize their efficiency, these generators are placed at strategic locations (windy regions for wind turbine, sunny

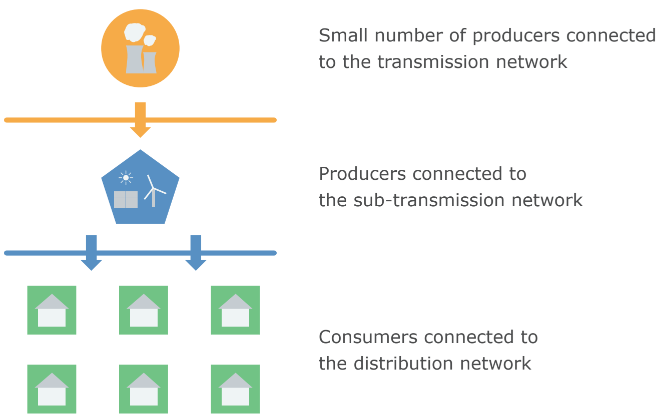

Fig. 1. Energy flow in historical electrical networks

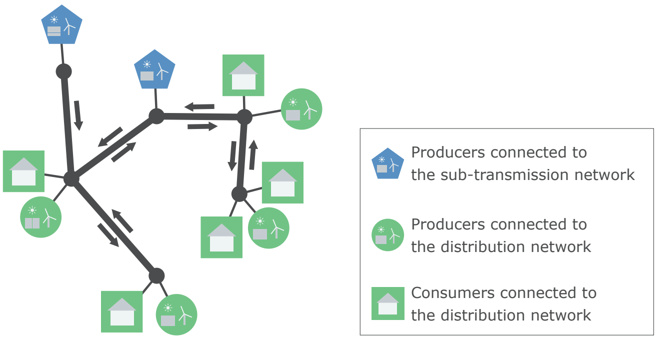

Fig. 2. Energy flow in future electrical networks

regions for photovoltaic panels, ...). Moreover, the production of these generators is unpredictable as it relies on the weather conditions.

C. Transition to the Smart Grid

We are then moving from an almost static electrical network with a radial structure, a unique control point and a stable production to an highly dynamic electrical network with multiple and distributed production points whose productions are unpredictable. Figure 2 represents the decentralized generators connected to the network and the expected exchanges of electricity between the different elements of the network.

Current management strategy are not adapted. It is necessary to rethink the way networks are operated. This introduces the notion of Smart Grid.

II. Smart Grid

"An automated, widely distributed energy delivery network, the Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring every- thing from power plants to customer preferences to individual appli- ances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level." [1]

This concept is an answer to the problematic induced by the massive integration of decentralized generators. As seen previously, electrical distribution network are operated globally, the most part of electricity is provided from one unique point and connected decentralized generators are underused. This approach is not compatible with the willingness of some entities to urge the apparition of new electricity suppliers and to remove monopolies[2].

Moreover, the demand in energy is growing fast. The worldwide energy demand is expected to rise by over 150% from 2010 to 2050 under the Energy Technology Perspectives 2010 (ETP 2010) Baseline Scenario and over 115% between 2007 and 2050 under the Blue Map Scenario [3].

In addition to this, more and more individuals install photovoltaic panels and wind turbines. Their productions are very variable and therefore can be greater or lower than the real consumption. To deal with this, a solution can be to install power banks which will store electricity and provide it to the consumer as needed. Another more effective solution can be to connect these generators directly to the main electrical network, thus other consumers can benefit from this green energy. Consumers are then expected to become producers (prosumers).

The automotive sector also play an important role in this transition. Electric cars are by nature moveable which means that an owner of an electric car can decide to load it one day at a point of the network and the other day at another. Moreover, using a smart algorithm, it is possible to use electric cars as producers able to inject powers in the network when the cars are not used. This introduces a notion of dynamic prosumers. These moves are unpredictable. It is therefore mandatory to provide flexibility and robustness to the electrical networks.

A. Characteristics of the Smart Grid

In the literature, the concept of Smart Grid is often represented by multiple characteristics [4]:

1) Supply/Demand Balancing: This characteristic is probably the most important and most studied one. With the advent of decentralized and unpredictable generators, it is necessary to have an active control of the balance between supply and demand. This characteristic is fundamental. There have been a lot of researches on it. As we introduce decentralized producers, it is important to maintain the balance between supply and demand in order to avoid blackouts. Balance can be made thanks to power banks and super-capacitors. Even if the massive introduction of electrical vehicles will result in increasing the complexity of the problem, it will also provide a lot of resources to balance supply and demand and to do load shifting [5].

2) Self-Healing: Whatever the distribution system, faults and power cuts are unavoidable.At best, it is possible to detect them before they happen[6]. A network operator must guarantee the security and ensure the effective functioning of the network. The Smart Grid must be able to detect and fix problems or at least inform a technician in case of a human intervention is necessary. Self-Healing is the capacity for an electrical network to detect and fix problems without the intervention of a human being. This issue has then to be treated for prevention. A solution, firstly proposed in the paper [7], is to allow the disconnection of a part of the network that can be autonomous. This implies the guarantee that if a problem occurs on the main distribution network, the isolated part will not be affected. The problem of keeping the system in good operating order can be represented as an optimization problem in which the number of well-served node is maximized [6], [8].

3) Losses Reduction: When the current in a line is too high, it increases the temperature of the line and therefore a part of the energy initially intended for consumers is dissipated through thermal exchanges with the air/water/soil surrounding the line. In long lines, the voltage magnitude is voluntarily raised high to prevent this. The equation (1) shows the relation between active power (P), reactive power (Q), the voltage (V) and the current (I).

$$P + i \cdot Q = V \cdot I^* \tag{1}$$

It can be seen that a highest voltage magnitude allows to provide the same amount of power with a lower current and therefore less losses. The combination of imposed voltages may have an important impact on the losses. While ensuring the other characteristics, the Smart Grid must minimize the losses.

Due to the line length and the Joule effect, there is a significant loss on electrical networks. This implies the need to produce more energy in order to counterbalance those losses. A solution to reduce the losses is to increase the voltage. Indeed, the increase of voltage enables to reduce the amount of current that pass while maintaining the power at the needed level. Most of times, the loss reduction is made through a topological reconfiguration of the network [9].

4) Minimization of Hardware Stress: The hardware connected to electrical networks are often quite expensive. This characteristic aims at avoiding premature wears by limiting solicitations made to the hardware. [10]

5) Voltage Regulation: The voltage regulation is the process of acting on the various equipment of the network to ensure that, at each point, the voltage magnitude is included in a pre-specified range. It is the act of choosing a set of voltage values in order to ensure that voltages at specific points will be in the admissible range ensured by the distribution network manager. This characteristic is important and hard to handle as it highly impact the flows of power. Currently, the voltage regulation of all energy provider nodes is centralized [11]. The main elements responsible for the voltage regulation are: transformers and decentralized producers [10]. This characteristic is particularly important and hard to handle as its complexity grows with the number of distributed producers and because of the non-predictability of the power produced by weather-dependent generators [12]. Anyway, we are moving toward the integration of massive distributed generators. In order to support these integrations, the voltage regulation system has to be distributed [11].

6) Environmental Friendliness: The Smart Grid concept comes from the will of consuming energy in a more intelligent way. It also implies that the production needs to be done in a smarter way. This characteristic corresponds to the will of encouraging the use of renewable energy [13].

B. The Smart Grid as a Complex System

Controlling the electrical distribution network is a complex problem in which there are dynamic elements affected by unpredictable events and for which it doesn't exist one unique good solution. These problems cannot be solved using a reductionist approach. Moreover, the design of systems aiming at solving complex problems often requires an expert of the domain who will tune the parameters to adapt the control system to the problem. Although, it may be viable for small sized problems, the Smart Grid is potentially at a worldwide scale and involves an important numbers of entities with unpredictable behaviors and potentially contradictory objectives, it is necessary to find an alternative solution to control it.

A complex system is a system composed of numerous interacting entities. The interactions between these entities are generally non-linear. These systems are subject to internal and external influences. Moreover, these systems cannot be designed using classical methods. The Smart Grid can be seen as a complex system as it contains heterogeneous elements, is impacted by external and internal factors (such as the weather and the behaviors of consumers), are observed through sensors and measurement tools and decisions must be taken locally for an overall balance [14]. Moreover, it is exposed to failures. It is therefore necessary to guarantee that these failures will impact as few as possible the electricity distribution.

C. Previous Works

Since 1998, a lot of works have been made in order to handle Smart Grid characteristics with a multi-agent system starting with the paper [15] in which the authors have focused on power balancing. In addition to this work, some approaches to solve power balancing problem were particularly interesting [13], [16], [5]. One common method for solving this problem is to make predictions on what will be consumed and produced in the next time window and to set up an auction system which is often centralized by a controller agent [17]. In more recent works, we also find approaches making use of electric vehicles [16] notably through load-shifting. Despite their interesting approaches, the presence of a controller agent that gathers auction informations is a potential damage source as it can lead to black-out if it fails. Even if the characteristic of self-healing is of lower importance compared to power balancing, this one has been well treated in many works [7], [8]. Firstly proposed in the paper [6], the objective of self-healing can be seen as the maximization of the number of well-served loads. The voltage regulation is a problem that is also hard to handle in Smart Grid as the integration of decentralized generators adds a lot of control points and therefore increases the complexity of the control of voltage. However, the work [11] leads the voltage regulation in smart grid to be considered as a local optimization problem thanks to multi-agent system. Anyway, the voltage regulation is made against one or multiple previously selected points. A great improvement would have been the possibility to change these points. Becoming more and more at the heart of debates, the characteristic of ecological friendliness is often considered by pushing coordinator agents to prefer energy from close and renewable sources [18]. The hardware stress minimization is the less considered characteristic. Indeed, it has only been taken into account in two papers published in 2012 [19], [5]. Their solution to minimize the number of solicitations made to hardware (such as On-Line Tap Changer and Switches) is to limit the number of requests that can be made per day without considering the rest of the network. One of the motivations for moving toward the concept of Smart Grid is to reduce the losses by bringing producers close to consumers. In addition to this, the losses reduction can be made by increasing the voltage where it is possible and by the reconfiguration of the network [20]. Despite the diversities of the approaches presented, it can be noticed the lack of some points which seems to be important, such as the openness of the system, the decentralization, the exponentially growing complexity and the automatic reconfiguration of the network.

III. Adaptive Multi-Agent System for the Smart Grid

The electrical distribution network evolution includes the massive integration of distributed generators, the bidirectional transit of electricity and increases the complexity of the control of the system. For these reasons, it is necessary that a control system consider all characteristics at the same time.

The Smart Grid is part of the Smart Cities challenge which consists in making the cities instrumented, interconnected and intelligent [21] and must therefore comply with other smart cities applications. Multiple Smart Cities applications involving multi-agent systems have shown encouraging results whether it is for modelling, simulation or problem solving [22]. The Smart Grid is one of those applications and has similar characteristics with other Smart Cities application.

A. *Multi-Agent System*

A Multi-Agent System is a system composed of interacting entities, named "agents", aiming at accomplishing a common task. These systems are notably used for simulation, coding and problem solving.

An agent is an entity that can be seen as perceiving its environment through sensors and acting on it with effectors [23]. An agent is autonomous, exists in an environment that it can partially perceive and on which it can act and has skills.

The types of agent depend on the application of the system. In the paper [24], the author proposes a series of principles aiming at helping the determination of agents in a system controlling an electrical network. Among them, three are particularly important to notice:

- **Physical Aggregation** This principle indicates that the composition of an agent must represent the set of physical objects it is connected to and it represents. In a coarse-grained system, an agent associated to a whole micro-grid should have a representation of all the elements it is made of;
- **Interaction** This principle indicates that agent interactions should be consistent with the structure of the network. In other words, it means that agents must interact with their nearest neighbors;
- **Scope of Physical Agents** This principle indicates that the agents scope and boundaries should be accorded to the physical elements they represent.

B. *Motivation for Using Adaptive Multi-Agent System*

Multi-agent system includes several properties which are interesting for the Smart Grid. Among them, in some multi-agent systems, there is the autonomy of agents which enables a self-adjustment and a reaction to changes without the intervention of external entities [25]. In the context of Smart Grid, it is particularly important to handle changes in the network without the intervention of operators especially for the voltage regulation on distributed generators and for the characteristic of self-healing. Moreover, despite the fact that centralized approach can facilitate the operating of small-scale systems and networks with unidirectional power delivery, the integration of a lot of Distributed Generators increases the complexity and multi-agent systems are particularly efficient for distributed problem solving. And finally, one of the requirements of the Smart Grid is the ability to handle connections and disconnections at run time, reinforcing then the idea of using a multi-agent system [10].

C. *Adaptation in Multi-Agent Systems*

Facing a changing environment, a system must be able to change the way it deals with it [26]. Adaptive multi-agent systems of a kind of multi-agent systems which have adaptation capacity which means that the behavior of the systems adapts to the problems and their dynamics. This is possible thanks to cooperation. The agents in an adaptive multi-agent system are cooperative. They tend to help their struggling neighbors even if it means that they temporarily need to abandon their own goal. The coordinated cooperative actions of the agents make the system cooperative with its environment. In addition to this, the approach imposes a strong constraint which is to not integrate the entire problem in the agents. This is consistent with the fact that agents only have a local perception. The solution to the problem faced by the system is expected to emerge from the auto-organization of agents.

Most of optimization and control algorithms are static and adapted to a specific problem. Therefore, they are not adapted to complex problems such as the ones inherent to the Smart Grid and more generally the Smart Cities. Moreover, usual ways to conceive systems force the designer to have important knowledge about the exact aim of the system and the exhaustive list about future interactions the system will be confronted to [27].

D. *Cooperation*

Cooperation is a social attitude followed by the agents. The interaction of some entities in order to solve a problem may require a kind of coordination and mutual assistance. In the context of multi-agent systems, this is referred to as cooperation, or cooperative agents, when their behavior results in helping the ones which are struggling the most. Agents act in the wider interest. In order for this kind of system to work, it is necessary that agents trust each other and that there is no ambiguity during inter-agents communications (Camps et al., 1998). The AMAS approach requires that each agent has a local goal that it tries to reach by executing local actions. It also requires that each agent has a cooperative attitude, in other words, the agent has to help its neighbor if this one is more struggling.

E. Emergence & Self-Adaptation

In every multi-agent system, a global function is expected from a set of local specifications. This global level property shouldnt be programmed into agents. Due to the openness characteristic, disruptive elements (environment, users or other agents) force the system to adapt itself and to constantly restructure itself to keep acceptable performances. This self-organizing characteristic can be seen in many domains. It corresponds to spontaneous emergence of a global coherence from local interactions of micro level initially independent components. The emergence appears from a self-adaptation between agents. Their cooperative behavior allows the appearance of a global function qualified of emerging. That is to say the appearance of a function which is not predictable by simply observing the local behaviors of entities in the system. "[...] On the one hand, the emergence presupposes that there is the appearance of something new-properties, structures, shapes or functions -, and on the other hand, it implies that it is impossible to describe, explain or predict these new phenomena in physical terms from the basic conditions set out below levels." [28] With a dynamic environment, the system must be able to change the way it acts in order to adapt itself. [26]

F. Benefits for the Smart Grid

Controlling the electrical network in an intelligent way is a complex problem in which numerous entities are involved and in during which multiple unpredictable events may occur. Therefore, the use of an adaptive multi-agent system is particularly relevant. An effective design of such system could bring multiple benefits.

First of all, it is known that classical optimization approaches have a non-linear complexity. It is generally not critical as studied problems often have a reasonable size. However, in the case of the Smart Grid, the amount of interacting elements is important and is expected to grow continuously. The locality of perceptions and actions in an adaptive multi-agent system helps the system to keep stable computation time even with larger instances [29]. The figure 3 shows an example of a state estimation made on a distribution network using an adaptive multi-agent system [4]. It can be seen on this figure that through local interactions the system is able to act at a global level.

Initially designed, controlled and managed by a single entity, the market liberalization implies the apparition of new independent management entities on these networks (such as companies which own solar parks and wind turbine farms or companies providing electrical cars). These entities may have different management strategy. Therefore, the control of the complete network cannot be left to a single entity. This is even more true with the connection of the network with the one of a neighbouring countries. The distribution of the control is then a mandatory step towards the Smart Grid, what reinforces the relevance of using an adaptive multi-agent system.

The resistance to disturbances and notably the maintaining of the function of electrical networks is also an essential feature of the Smart Grid. The autonomy of agents and their locality of perceptions and actions could allow the system to maintain a functional equilibrium. The figure 4 shows the adaptation capability of an adaptive multi-agent system against perturbation during a state estimation process.

Finally, it is known that "the generation of electricity takes an important role in the global warming which is one of the greatest threats to human and animals health" [30]. As seen in the previous part, multi-agent systems are efficient to handle many characteristics of Smart Grid. Moreover, the AMAS theory relies on the same principles than multi-agent systems and therefore benefits of the same advantages. Anyway, we often see multi-agent systems composed of generally one agent controlling others. Despite the fact that classical multi-agent systems will work most of the time, they generally relies on

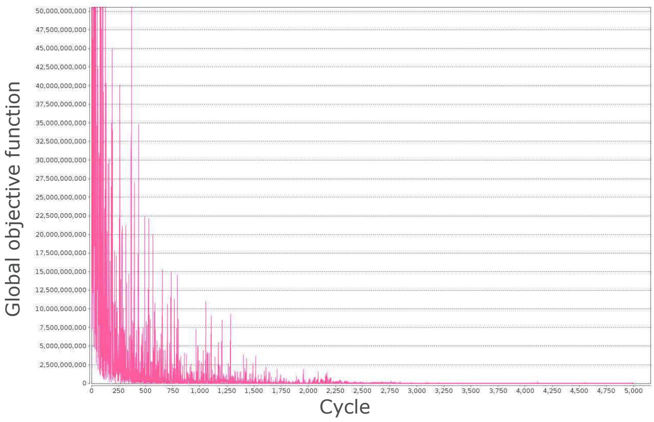

Fig. 3. Global State Estimation using an Adaptive Multi-Agent System

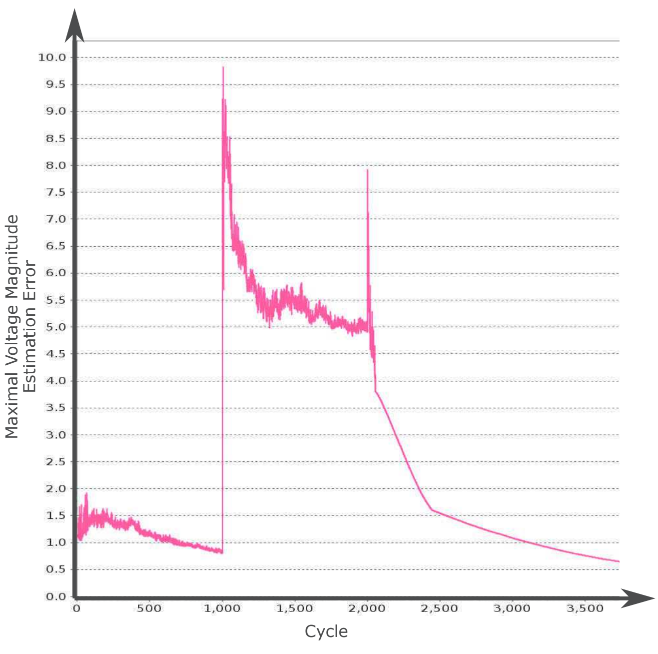

Fig. 4. Robustness of an Adaptive Multi-Agent System against a Perturbation

one component: the agent coordinator [13]. If this one fails, the whole system may fail too. With the adaptive approach, agents dont rely on one pre-specified chief. Agents cooperate with each other providing a more robust and flexible system which perfectly fits with the Smart Grid problems and thus may be able to support future developments of electrical distribution networks.

IV. Conclusion

In this paper, after having characterized the electric distribution problematic, we have discussed and shown how Adaptive Multi-Agent Systems are relevant to solve problems inherent to the concept of Smart Grid and notably are able to adapt themselves to the evolution of the way we produce and consume electricity. For this, we are working on the realization of a system able to solve problems that cannot be solved using classical methods. In addition to considering the smart grid characteristics, this approach allows to handle new components at runtime and facilitate the transition to a more local use of energy. Finally, the telecommunication issues should be taken into account. Despite the relatively novelty of the Adaptive Multi-Agent System approach, it has proven its capacity to solve complex problems efficiently. By its openness and its adaptation ability, the Adaptive Multi-Agent System theory seems to be a suitable approach for controlling distribution networks.

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